THE ASTROPHYSICAL JOURNAL, 253:L77–L82, 1982 February 15

ULTRAVIOLET OBSERVATIONS OF THE 1980 ECLIPSE OF THE SYMBIOTIC STAR CI CYGNI

ROBERT E. STENCEL[1]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards
ANDREW G. MICHALITSIANOS[1]
Laboratory for Astronomy and Solar Physics, NASA Goddard Space Flight Center
MINAS KAFATOS[1]
Department of Physics, George Mason University, Alexandria, Virginia
AND
ALEXANDER A. BOYARCHUK
Crimean Astrophysical Observatory, U.S.S.R. Academy of Sciences
Received 1981 January 19; accepted 1981 October 29

ABSTRACT

Secular and eclipse variations of UV lines and continua during the course of nearly a full orbit of the symbiotic binary CI Cygni are presented. High-excitation resonance lines have brightened on an orbital time scale and show minimal effects of eclipse, while intercombination lines have faded and show pronounced but nontotal eclipse effects. The data are discussed in terms of mass transfer from the extended cool envelope of the red giant to a compact secondary. The formation of an accretion disk is a transitory phenomenon in which viscosity eventually dissipates the disk over orbital time scales. A large-scale low-density nebula explains the intercombination line emission, whereas the resonance line emission apparently arises in a large volume emitting region, possibly formed through shock collision from interacting stellar winds from the primary and secondary. Mass transfer rates are briefly discussed.

Subject headings: stars: combination spectra — stars: eclipsing binaries — stars: mass loss — stars: winds

I. INTRODUCTION AND OBSERVATIONS

The complex but quasi-regular light variations of the symbiotic star CI Cyg led B. F. Whitney (cited by Aller 1954) to propose an 855 day period. Subsequent observations verify this period (cf. Hoffleit 1968; Mattei 1978; Belyakina 1976, 1979; Huruhata 1980). These periodic phenomena can be understood as eclipses, and we monitored the 1980 event with the *International Ultraviolet Explorer* (*IUE*). This *Letter* reports the ultraviolet observations, which shed new light on the nature of the object and its wider implications for the understanding of the symbiotic phenomenon. A more detailed report presenting merged optical and UV information will be presented elsewhere.

In addition to the 1980 series of 10 sets of low-resolution (6 Å) spectroscopic observations covering the 1150–3200 Å interval, archival data obtained with the *IUE* satellite (Boggess *et al.* 1978) provide coverage over nearly a full orbit, starting in early 1979. The light curve suggests late stages of decline toward quiescence following the 1975 eruptive (3 mag) outburst. Table 1 lists the specific observations and predicted times of eclipse. The out-of-eclipse spectrum shows numerous emission lines in the 1150–2000 Å interval, and a few additional emission lines in the 2500–3200 Å interval superposed on top of a bright continuum rising from about 2500 Å toward the longwave cutoff near 3250 Å (Fig. 1). On the basis of calibrated optical observations (Blair *et al.* 1981) showing a Balmer emission jump at 3646 Å, we ascribe the continuum to Balmer free-bound radiation. Bands of molecular OH absorption (Diecke and Crosswhite 1962) are superposed on the continuum of 3064 and 2875 Å, indicating extended material along the line of sight.

The spectral data were analyzed using the guest observer tapes supplied by the image processing center at *IUE* via an interactive reduction system in use at the Joint Institute for Laboratory Astrophysics (JILA). We have adopted the low-dispersion photometric calibration supplied with the data tapes, based on Bohlin *et al.* (1980) and updates thereto.

[1]Guest Observer, *International Ultraviolet Explorer.*

TABLE 1

IUE OBSERVATIONS OF CI CYGNI

Year/Day Number	JD + 2,440,000	FES Counts	Images[a]	Exposure (minutes)
1979/007	3881	404	SWP 3817L	20
			LWR 3396L	30
1979/180	4054	359	SWP 5672L	24
			LWR 4916L	12
1979/283	4157	...	SWP 6818H	90
			LWR 5801L	15
1980/030	4269	287	SWP 7818L	60
			LWR 6831L	20
1980/076	4315	327	SWP 8264L	12
			LWR 7206L	15
1980/101 .... (first contact)	4340	...	...	...
1980/107	4346	255	SWP 8774L	24
			LWR 7518L	15
1980/116	4355	242	SWP 8826L	24
			LWR 7603L	20
1980/127 .... (second contact)	4366	...	...	...
1980/135	4374	231	SWP 8993L	25
			LWR 7752L	25
1980/146	4385	...	SWP 9116L	21
			LWR 7833L	20
1980/158 .... (mid-eclipse)	4397	...	...	...
1980/183	4422	230	LWR 8157L	25
			SWP 9411L	25
1980/205 .... (third contact)	4444	281	SWP 9573L	60
1980/214	4453	296	SWP 9663L	25
			LWR 8408L	20
1980/231 .... (fourth contact)	4470	286	SWP 9830L	20
			LWR 8542L	20
1980/319	4558	260	SWP 10602L	20
			LWR 9303L	20
1981/087	4692	285	SWP 13602L	12
			LWR 10229H	45

[a] Exposures through large aperture.

II. ANALYSIS

a) Secular Variations

Figures 2*a*–2*e* display the light curves of the optical (V), the ultraviolet lines (integrated flux), and ultraviolet continuum (monochromatic flux) as a function of Julian Date and orbital phase (with respect to the 1980 mid-eclipse). The unblended intercombination lines (Figs. 2*a* and 2*b*) exhibit clear evidence of the eclipse, as predicted, plus a secular decline inversely related to excitation. This can be seen in N IV], N III], Si III], O III], and C III]. The permitted lines (Figs. 2*d* and 2*e*) increase with time in the case of N V and He II, but strongly decrease in the case of Mg II. The situation for C IV is unfortunately muddied by strong saturation effects in the data. These lines collectively exhibit a relation between secular change and excitation (Fig. 3, top). The optical and Balmer continuum, as well as the Bowen fluoresced lines of O III (Fig. 2*c*), are best discussed in the context of depth of eclipse.

b) Depth of the 1980 Eclipse

Figure 3 (bottom) represents an estimate of the depth of eclipse in each feature shown in Figures 2*a*–2*e*, obtained by a ratio of the minimum signal near mid-eclipse to an interpolated value at the time of mid-eclipse defined by the overall secular trend (i.e., as though eclipse did not occur). Except for He II and the Balmer continuum, the eclipse was *deeper* than the optical eclipse in the intercombination lines, but *shallower* than optical in the resonance lines! In fact, it is consistent with the error limits in the integrated flux measurements to claim that virtually no eclipse occurred in the N V and Mg II lines, compared to the Balmer continuum which seems to have been totally eclipsed (Fig. 2*c*).

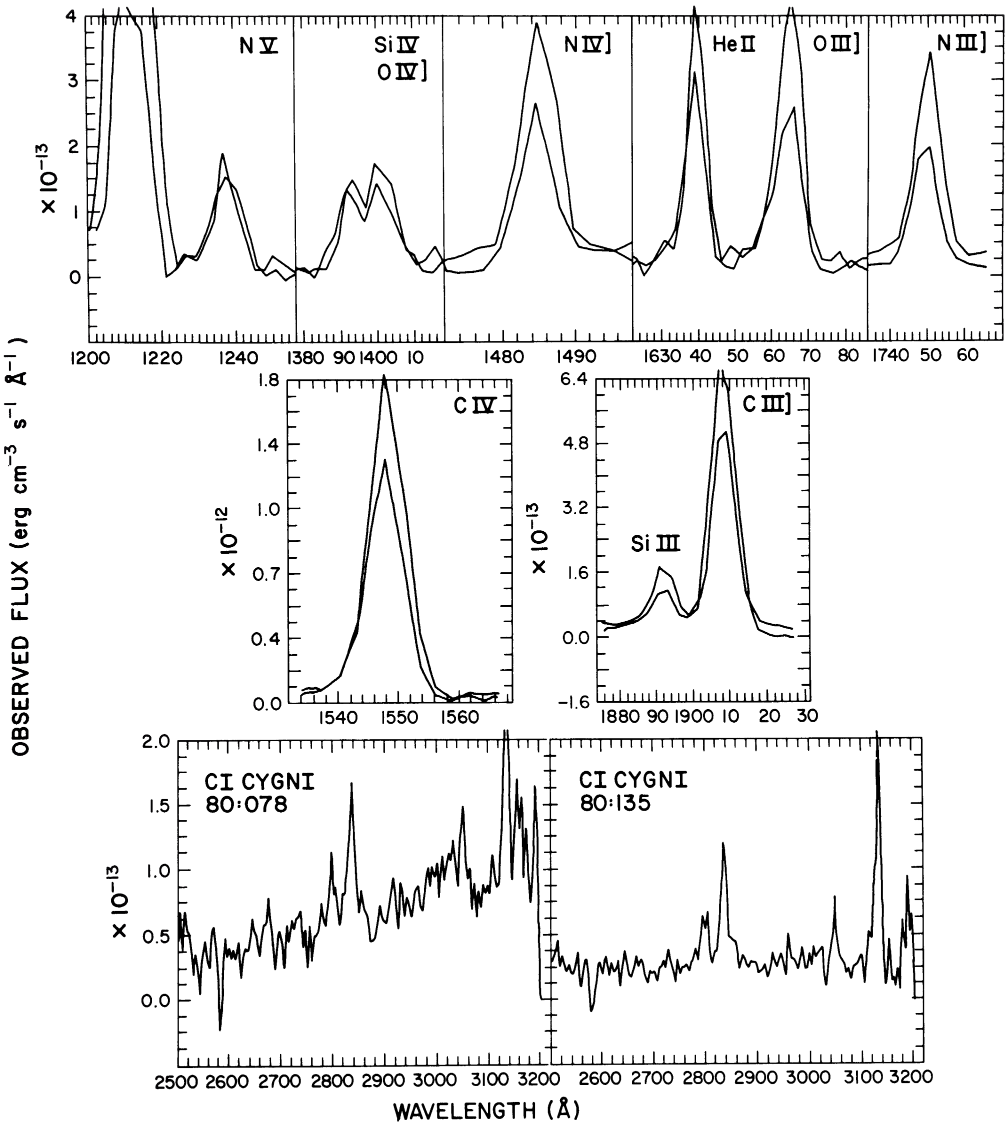

FIG. 1.—Variations in the UV spectrum of CI Cygni between 1980 March (ingress, brighter lines) and 1980 May (near mid-eclipse)

The mid-UV lines of O III, which are capable of being fluorescently pumped by He II λ304 photons and are insensitive to the eclipse (Fig. 2*c*), suggest the presence of extended material surrounding CI Cygni. The presence of intercombination lines and the absence of strong forbidden line emission constrains the nebular density to the 10^4–10^9 cm^{-3} regime. The cross section for He II λ304 absorption (4×10^{-19} cm^2) implies photon path lengths of 10^{15}–10^{10} cm. If He II is optically thick, these are *lower limits*. The larger dimensions are consistent with the lack of eclipses and comparable to the orbital separation—a natural dynamical scale size for the system. The minimum eclipse duration, $0.12P$, indicates $R_M = 0.38a$, which is close to the Roche limit. For a plausible range of total mass in the system (3–7 $M_\odot$), an orbital separation of 3.8–5.0 $\times$ 10^{13} cm is implied.

The behavior of He II λ1640 is somewhat maverick in that, unlike other permitted lines, it shows deep eclipses. There is also indication that the higher excitation intercombination line, N IV], shows deeper eclipse than all of the lower excitation ones.

III. INTERPRETATION

We believe the data are consistent with a binary star model involving an extended but aging accretion disk about the hot companion, plus nebular material possibly originating from the M giant outer atmosphere in a

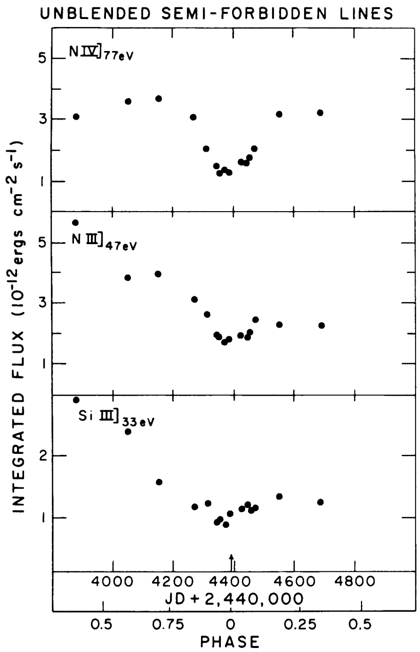

FIG. 2*a*

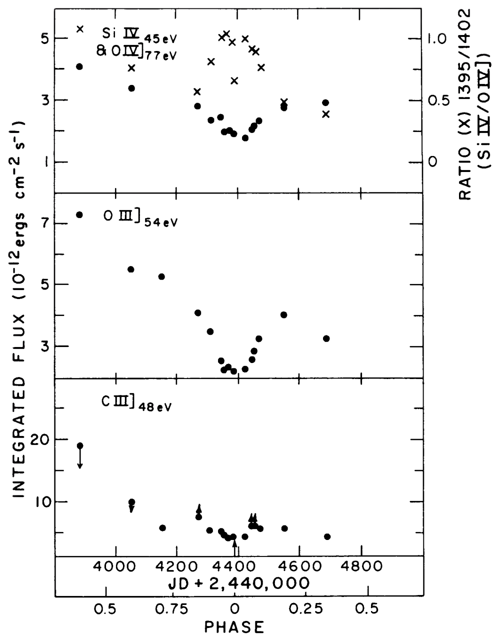

FIG. 2*b*

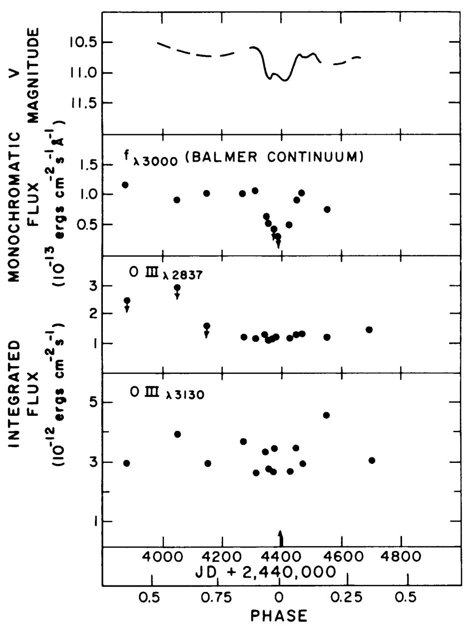

FIG. 2*c*

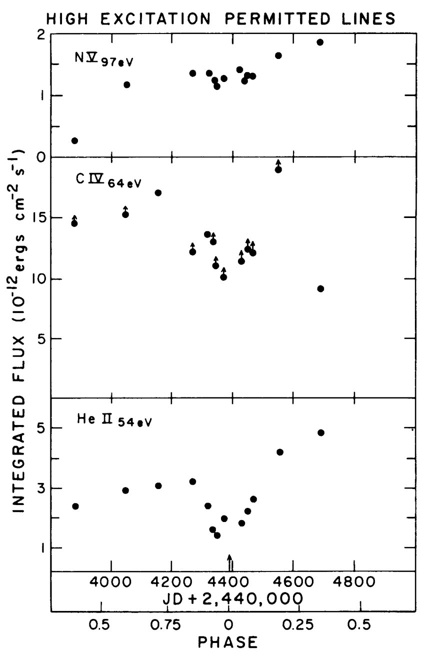

FIG. 2*d*

FIG. 2.—(*a*–*e*) Secular and eclipse variations of integrated line fluxes and continuum brightness in CI Cygni between 1979 January and 1981 April.

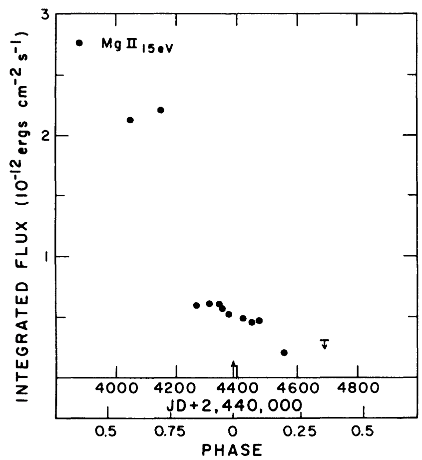

FIG. 2*e*

warm, dense wind. The secular variations can be used to rule out a simple expanding nebular shell, because the higher excitation *resonance* lines are seen to increase in strength. The *intercombination* lines decrease, contrary to expectation in a nebula with radially decreasing density. We associate the intercombination lines (Si III], N III], C III], O III], and N IV]), He II, and the Balmer continuum with accretion phenomena near the hot star itself. The lack of eclipses in the resonance lines (Mg II, Si IV, C IV, and N V) suggests either an extended thin shock region between the stars producing the observed emission measures, or an anisotropic ionization structure, e.g., over the poles of the hot object.

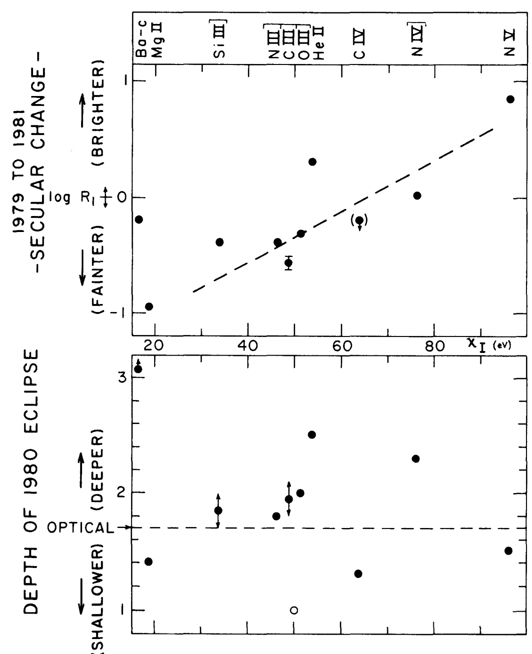

FIG. 3.—Secular and eclipse variations of features in the UV spectrum of CI Cygni as a function of excitation potential, χ_I in eV. The open circle indicates the essentially uneclipsed Bowen O III lines.

We note that none of the intercombination lines is fully eclipsed. Their region of formation apparently envelopes both stars in part, with a Strömgren-like ionization structure centered around the hot object and N IV] showing the deepest eclipse. He II λ1640 behaves like an extreme intercombination line in this respect, being strongly eclipsed.

We suggest that the fully eclipsed Balmer continuum originates in the exterior of a thick but aging accretion disk, first demonstrated to exist during the 1975 outburst by Webbink and Kenyon (1981). The estimated total flux in the Balmer continuum (2500–3646 Å) was 8×10^{-11} ergs cm^{-2} s^{-1} in early 1980. Adopting a distance of 1500 pc and $E_{B-V} = 0.5$ mag (Mikolajewska and Mikolajewski 1980), we estimate the luminosity in the Balmer continuum to be about 67 $L_\odot$, which includes a factor of 12 dereddening but *no* correction for disk inclination, since we postulate that the continuum arises from the final scattering on the exterior of a geometrically thick disk (aspect ratio 1:5; Bath 1981). Assuming the disk radiation is recombination dominated, about one-third of the total luminosity emerges in the Balmer continuum, with a substantial flux in the yet-to-be observed Lyman lines and continuum. Because of various uncertainties, we can only establish a lower limit to the disk luminosity of 200 $L_\odot$. We have further developed scaling laws for accretion disks (cf. Kafatos, Michalitsianos, and Feibelman 1982) which relate disk dimensions and luminosities to accretion rates:

$$L_{\rm disk} \approx 10\dot{M}_{-8} M R_9^{-1}, \qquad (1)$$

and

$$T_{\rm bl} \approx 3 \times 10^5 M^{1/4} \dot{M}_{-8}^{1/4} R_9^{-0.75} \approx 5 T_{\rm disk}, \qquad (2)$$

where R_9 is the inner (boundary layer) radius in 10^9 cm units, M is mass ($M/M_\odot$), and $\dot{M}_{-8}$ is the accretion rate in 10^{-8} $M_\odot$ yr^{-1} units. The Balmer continuum formation (10,000–20,000 K) suggests that $T_{\rm bl} \approx 50{,}000$ to 10^5 K (eq. [2]). We can eliminate $M\dot{M}_{-8}$ from equations (1) and (2) to solve for R_9 and thus delimit the companion star dimension. The lower limit is several times 10^8 cm, suggesting that a 1 $M_\odot$ white dwarf companion might exist. However, we stress that this is a lower limit since all contributions (lines, inclination, dereddening, etc.) to the total disk luminosity may not have been included. A white dwarf companion would require 10^{-7} $M_\odot$ yr^{-1} to satisfy the disk luminosity, while a main-sequence-sized companion ($R_9 = 100$) would require 10^{-5} $M_\odot$ yr^{-1}. This latter rate would produce super-Eddington flows with a white dwarf (Bath 1977), potentially mimicking behavior seen during the 1975 outburst. If somehow the entire M star outer atmosphere were transferred on a dynamical time scale (orbital period), it would provide 10^{-7} $M_{\odot}$ yr^{-1} (based on a $1.5R_M$ extended atmosphere at 10^{10} cm^{-3} particle density). Further tests to discriminate between white dwarf and main-sequence accretors are much needed.

We acknowledge the outstanding assistance provided by the resident astronomers and telescope operators of the *IUE* observatory. We also thank Ron Webbink for his extensive comments which improved our analysis. Ted Snow provided a valuable communications link with Dr. Boyarchuk, and we thank R. Wing, J. Sahade, M. Plavec, and D. Lambert for obtaining early observations of CI Cygni with the *IUE*.

REFERENCES

Aller, L. 1954, *Pub. Dom. Ap. Obs. Victoria*, **9**, 321.
Bath, G. 1977, *M.N.R.A.S.*, **178**, 203.
______. 1981, in *Proc. North American Workshop on Symbiotic Stars*, ed. R. Stencel (Boulder: JILA), p. 20.
Belyakina, T. 1976, *Inf. Bull. Var. Stars*, No. 1169.
______. 1979, *Inf. Bull. Var. Stars*, No. 1602.
Blair, W., Stencel, R., Feibelman, W., and Michalitsianos, A. 1981, *Bull. AAS*, **12**, 869.
Boggess, A., *et al.* 1978, *Nature*, **275**, 372.
Bohlin, R., Holm, A., Savage, B., and Snijders, M. 1980, *Astr. Ap.*, **85**, 1.
Diecke, G., and Crosswhite, H. 1962, *J. Quant. Spectrosc. Rad. Transf.*, **2**, 97.
Hoffleit, D. 1968, *Irish Astr. J.*, **8**, 149.
Huruhata, M. 1980, *Inf. Bull. Var. Stars*, No. 1896.
Kafatos, M., Michalitsianos, A., and Feibelman, W. 1982, *Ap. J.*, submitted.
Mattei, J. 1978, *J.R.A.S. Canada*, **70**, 325.
Mikolajewska, J., and Mikolajewski, M. 1980, *Acta Astr.*, **30**, 347.
Webbink, R., and Kenyon, S. 1981, private communication.

A. BOYARCHUK: Crimean Astrophysical Observatory, p/o Nauchny, Crimea 334413, U.S.S.R.

M. KAFATOS: Department of Physics, George Mason University, 4400 University Drive, Fairfax, VA 22030

A. MICHALITSIANOS: Code 685.1, NASA Goddard Space Flight Center, Greenbelt, MD 20771

R. STENCEL: Joint Institute for Laboratory Astrophysics, University of Colorado, Mail Code 440, Boulder, CO 80309